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IMPROVEMENT OF ABRASIVE AND EDGE CUTTING MACHINING EFFICIENCY THROUGH THEORETICAL ANALYSIS OF PHYSICAL CONDITIONS

MOHAMMAD ESSA MATARNEH

Department of Mechanical Engineering, Al-Balqa Applied University, Al-Huson University College, Al-Huson-Irbid, Jordan

ABSTRACT

This research theoretically illustrates the effect of reducing the angle of entry of the abrasive grain into the work material on energy consumption in grinding operations. This is achieved by changing the shape of the sliding micro- fractures of cutting grains at up grinding and down grinding along the cutting wheel periphery, grinding with a reduced force of friction between the cutting grain and work material, and with the reduced negative rake angle of the cutting grain by using super hard synthetic materials wheels. In edge-cutting machining, they include the application of tangential turning, cut-down milling with an end mill. The ranges of change in the nominal angle of friction between the cutting grain and the work material and the negative rake angle of the cutting grain, under which the energy consumption in machining reaches the lowest values, were determined theoretically. It is shown that the nature of change in the energy consumption in machining is due to a change in the nominal shear angle of the work material. It is established that infinite values of the energy consumption in machining were achieved at a nominal shear angle of the work material equal to the angle of entry of the abrasive grain into the work material. Therefore, it is necessary to increase the nominal angle of shear on the work material by reducing the intensity of friction in the cutting area and the cutting grain negative rake angle. Theoretical determination of the conditions required for increasing the efficiency of machining by increasing the ratio of the tangential cutting force and thrust force, as well as the ratio of the shear thickness to the corner radius of the cutting tool, which reduce the friction in the cutting area and the rake angle of the cutting tool was achieved. It has been demonstrated that it is possible to achieve a reduction in the cutting force while improving the accuracy of grinding machining, by reducing the energy consumption in machining and substantially increasing the speed of the wheel. This predetermines the effectiveness of the use of grinding in finishing operations.

***KEYWORDS:** Machining, Energy Consumption in Machining, Grinding, Abrasive Grain, Cutting Tool, Cutting Force, Superhard & Synthetic Materials*

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Original Article

INTRODUCTION

Target Setting

In finishing machining applications of machined parts, grinding is used to reduce the cutting forces and improve the accuracy and the roughness of the machined surface. In most cases, grinding is considered the final step, ensuring the required quality and accuracy of is achieved on machined surfaces. However, as practice shows, grinding is characterized by high heat stress due to the intense friction of the cutting grains and the bonding material of the grinding wheel with the worked material. This leads to burns, micro cracks and other temperature defects on the machined surfaces, which cannot always be eliminated by subsequent abrasive or diamond lapping.

Such consequences can be overcome by reducing the force and heat stress in the grinding process. It should be noted that currently an extensive practical experience has been accumulated in order to solve this problem. At the same time, the physical conditions for reducing the force and heat stress in the grinding process, as well as edge cutting machining processes are not sufficiently disclosed in the scientific and technical literature in terms of changing the mechanics of shearing, micro-cuts formation, and reducing the energy consumption in machining.

LITERATURE REVIEW AND PROBLEM IDENTIFICATION

Research has shown the defining role of the friction processes in the formation of the force stress of the processes of abrasive and edge cutting machining, based on performed calculations of the strain-stress state of the cutting area[1-5]. The necessity of using more effective process media and more advanced designs of grinding wheels with high cutting ability (discontinuous grinding wheels of super hard synthetic materials), in addition to advanced methods of grinding wheel dressing are well established reducing techniques[6-8]. Furthermore, it is also effective to apply wear-resistant coatings to the working surface of cutting edge tools. Finally, researchers have shown the possibility of reducing the force stress in the cutting process by to the choice of rational values of the angle of entry of the cutting grain into the work material in abrasive machining [9-11]. However, as a rule, these problems are solved experimentally. Thus providing only isolated solutions for quite particular machining conditions, and limiting the abstract concept of the regularity of the mechanics of the cutting process. Therefore, the present research develops further on previous research [11], in which a deeper theoretical analysis of the conditions for reducing the force stress of the abrasive and edge cutting machining processes was carried out.

The research objective is the theoretical determination of the main elements that will increase the effectiveness of abrasive and edge cutting machining, by achieving a reduction in the energy consumption in machining, focusing on changes in the kinematics of the formation of shearing micro-cuts in grinding.

PROCEDURES AND METHODS

Research has shown analytically a correlation for determining the energy consumption in machining equal to the nominal cutting stress σ, which is obtained from the position of micro-cutting processes with a grinding wheel grains and chip formation without taking into account the friction of the wheel bonding material with the work material [11]:

$$\sigma = \frac{2 \cdot \tau_{shear} \cdot \cos\alpha \cdot \cos\psi_1}{[1 - \sin(\alpha + \psi_1)]} \tag{1}$$

where τ_{shear}: ultimate shear stress of work material, N/m^2; α: angle of entry of abrasive grain into work material; $\psi_1 = \psi + \gamma$; ψ: nominal friction angle of cutting grain with work material ($tg\psi = f$: coefficient of friction); γ: negative rake angle of cutting grain.

As follows from equation (1), energy consumption in machining σ can be reduced mainly by increasing the denominator, by reducing the trigonometric function $\sin(\alpha + \psi_1)$, i.e. by reducing the sum of angles $(\alpha + \psi_1) = (\alpha + \psi + \gamma)$. Therefore reducing angles α, ψ and γ, which is achieved by changing the shape of the shearing micro-cuts with cutting grains: transition from the up grinding with the periphery of a wheel (α >0, Figure 1.A) to the kinematic diagrams of face grinding and down grinding with the periphery of a wheel, achieving the conditions α =0 and α <0 (Figure 1.B), by

decreasing in the friction intensity of the cutting grain with the work material and by decreasing in the negative rank angle of the cutting grain γ through the use of wheels of superhard synthetic materials with a high cutting edge sharpness, and also through the use of effective methods for wheel dressing when machining i.e. timely removall of glazed grains from the working surface of wheel. As shown, the greatest effect of machining can be achieved when grinding is carried out according to a pattern that realizes the condition α <0, i.e. according to a down grinding pattern, when thickness of the cut at the initial moment takes the greatest value and decreases as the cutting grain is cutting into the work material.

It should be noted that the sum of angles $(\alpha + \psi_1)$ should be less than 900. Otherwise, cutting and, consequently, microchipping and material removal by grinding is unfeasible, since $\sin(\alpha + \psi_1) \rightarrow 1$, and the energy consumption in machining will be $\sigma \rightarrow \infty$, which only leads to elastic-plastic deformation of the work material without cutting it. Which might explain the high force and heat stress of grinding with the periphery of a wheel, since it is possible that the sum of angles is equal to $(\alpha + \psi_1) \rightarrow 90^0$, and $\sigma \rightarrow \infty$. This also explains the effectiveness of the use of face grinding, at which the condition α =0 is realized, therefore the sum of angles $(\alpha + \psi_1)$, and accordingly, the energy consumption in machining σ are both reduced.

Due to this physical effect of machining, the pattern for edge sharpening of cutting carbide tools with face wheels made of superhard synthetic materials with small values of the negative rank angle of the cutting grain γ has been widely used in practice. In addition, superhard synthetic materials have the lowest coefficient of friction f (the lowest nominal friction angle of the cutting grain with the work material ψ), which helps to reduce the trigonometric function $\sin(\alpha + \psi_1)$ in equation (1), therefore lowering energy consumption in machining σ. As a result, grinding will produce machined surfaces with high quality while eliminating the formation of various temperature defects (burns, microcracks and others).

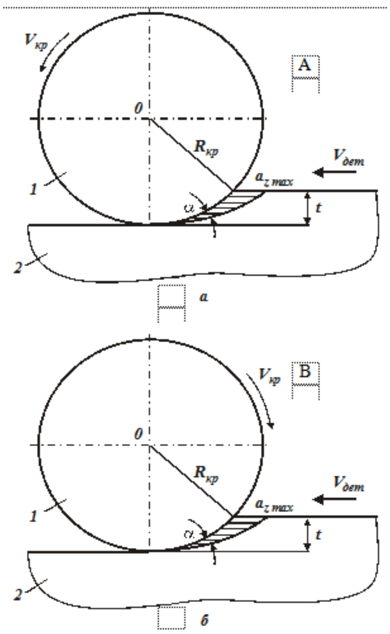

Figure 1: Design Diagrams of Grinding: A: Up Grinding (Case α >0); B: Down Grinding (When α <0); 1: Grinding Wheel; 2: Work Piece

As noted above, the greatest effect of machining is achieved at up grinding, when the angle α <0. In this case, the sum of angles $(\alpha+\psi_1)$ and the trigonometrical function $\sin(\alpha+\psi_1)$, and consequently, the denominator of equation (1) are reduced. The trigonometric function $\cos\alpha = \cos(-\alpha)$ in the numerator of the equation (1) is also reduced, which creates an additional effect of reducing the energy consumption in machining σ .

It should be noted that equation(1) implies the ambiguous nature of the change in energy consumption in machining σ with increasing angle ψ_1. By reducing the denominator of the equation, the energy consumption in machining σ increases and at value $\psi_1 = 90^0 - \alpha$ tends to infinity. The trigonometric function $\cos\alpha$, in the numerator of the equation decreases with increasing angle ψ_1 and at value $\psi_1 = 90^0$ equals to zero value. Therefore, there must be an extremum of the function σ within the range of $0 < \psi_1 < 90^0$.

To determine the extreme nature of the change in the energy consumption in machining σ from the angle ψ_1, it is necessary to introduce the function σ to the necessary extremum condition ($\sigma'_{\psi_1} = 0$).

For ease of analysis the equation (1) taking into account the trigonometric transformation $\sin(\alpha+\psi_1) = \sin\alpha \cdot \cos\psi_1 + \cos\alpha \cdot \sin\psi_1$ can be represented as follows:

$$\sigma = \frac{2 \cdot \tau_{сдв}}{\left(\frac{1}{\cos\alpha \cdot \cos\psi_1} - tg\alpha - tg\psi_1 \right)} . \tag{2}$$

Then

$$\sigma'_{\psi_1} = \frac{-2 \cdot \tau_{shear}}{\left(\frac{1}{\cos\alpha \cdot \cos\psi_1} - tg\alpha - tg\psi_1 \right)^2} \cdot \left(\frac{\sin\psi_1}{\cos\alpha \cdot \cos^2\psi_1} - \frac{1}{\cos^2\psi_1} \right) = 0 . \tag{3}$$

Solving the obtained equation (3), the extremal angle value ψ_1 is determined:

$$\sin\psi_1 = \cos\alpha . \tag{4}$$

Analysis has shown that the second derivative σ''_{ψ_1} at the extreme point takes a negative value. Therefore, the function maximum σ takes place at the extremum point.

The nature of the change in the function $\sigma / 2\tau_{shear}$, determined by equation (1) with increasing angle ψ_1 is summarized in Table 1 and in Figure 2. As it can be seen, regardless of the angle value α , the function $\sigma / 2\tau_{shear}$ takes an infinite value at an angle $\psi_1 = 90^0 - \alpha$. Thus, for angle α = 0, the infinite value of the function $\sigma / 2\tau_{shear}$ is achieved at value $\psi_1 = 90^0$ (Figure 2.A); for angle α =450 is respectively achieved at value $\psi_1 = 45^0$ (Figure. 2.B); and for angle α = –450 is respectively, achieved at value $\psi_1 = 135^0$ (Figure 2.C).

Table 1: Design Values of Function $\sigma / 2\tau_{shear}$

$\psi_1,^0$	**0**	**30**	**45**	**60**	**90**	**135**
α = 0	1	1.73	2.41	3.72	∞	–
α = 450	2.41	18	∞	10.1	0	–
α = –450	0.41	0.48	0.5	0.47	0	∞

There is no extreme value for the function $\sigma / 2\tau_{shear}$ at positive values of angle α (α =0; α =450), it is at negative values of the angle α, and, according to equation (4) and Table 1 for angle α = –450 it is achieved at angle $\psi_1 = 45^0$.

At angle value $\psi_1 = 90^0$ the function $\sigma / 2\tau_{shear}$ takes a zero value for both positive and negative values of angle α (except for case α =0).

The established nature of the change in the function $\sigma / 2\tau_{shear}$ is due to a change in the nominal shear angle of the work material β, which is generally described by an analytical relation [11]:

$$\beta = \frac{\pi}{4} + \frac{\alpha - \psi_1}{2}. \qquad (5)$$

With increasing angle ψ_1, the angle β is reduced, predetermining the increase in the function $\sigma / 2\tau_{shear}$. At an angle value of $\psi_1 = 90^0 - \alpha$, at which the function $\sigma / 2\tau_{shear}$ takes an infinite value, the nominal angle of shear of the work material $\beta = \alpha$. In this case, the angle β is equal to the angle of entry of the abrasive grain into the work material α, i.e. there is no process of cutting and chip formation, and there is only the process of elastic-plastic deformation of the material without separation of chips.

At angle values of $\psi_1 > 90^0 - \alpha$ will result in angles where $\beta < \alpha$. Consequently, in this case too there is a process of elastic-plastic deformation of the material without separation of chips. This is consistent with the design function data $\sigma / 2\tau_{shear}$ for the cases α =0 and α =450, given in Table 1 and Figures 2.A and 2.B. As it can be seen, the cutting process and chip formation occur the angle change in the range, and the process of elastic-plastic deformation of the material without separation of chips occurs in the range $\psi_1 > 90^0 - \alpha$ (Figure 2.A and 2.B).

At angle α = –450 with increasing angle ψ_1, according to dependence (5), the nominal angle of shear of the work material β is reduced and at value of the angle $\psi_1 = 45^0$ becomes zero, i.e. in this case, the process of cutting and chip formation turns into the process of elastic-plastic deformation of the material without separation of chips. At angles $\psi_1 > 45^0$, the angle assumes negative values, which excludes the possibility of the cutting process and chip formation. Consequently, there is the cutting and chip formation process when angle change in the range of $\psi_1 < \alpha^*$, where the angle α^* is determined from equation (4), and the process of elastic-plastic deformation of the material without separation of chips takes place when angle change in the range of the $\psi_1 > \alpha^*$. Thus, using the analytical relation to determine the nominal angle of shear of the work material β, it is possible to scientifically justify the nature of the change in the

function $\sigma / 2\tau_{shear}$.

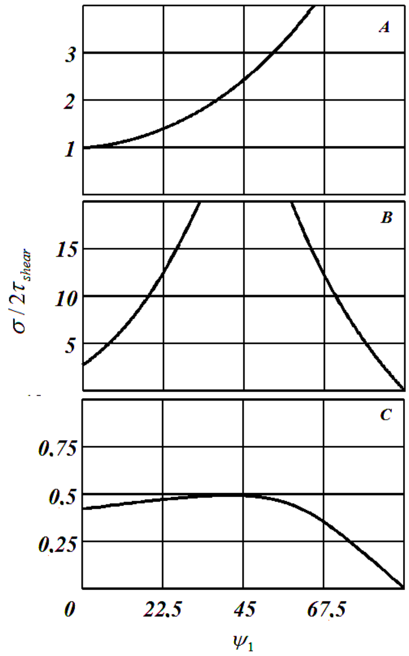

Figure 2: Nature of Change in Function $\sigma / 2\tau_{shear}$ Depending on Angle ψ_1 ;
A: α =0; B: α =45^0; C: α = –45^0

Clearly, the energy consumption in machining increases as the angle α increases. The lowest values of σ in this case are achieved at an angle of α =–450. This suggests that the denominator prevails in equation (1), since it determines the conditions for the implementation of the cutting and chip formation processes, and accordingly, the nature of the change in the energy consumption in machining σ from angles ψ_1 and α .

It is also known that, similar to grinding, turning should be effectively carried out with a negative angle α . This explains the effectiveness of the practical use of tangential turning, when cutting is carried out with a tapered thickness of cut, varying from the maximum value to zero.

Traditional turning patterns achieve the condition where α =0. In this case, equation (1) can be simplified and presented as follows:

$$\sigma = \frac{2 \cdot \tau_{shear}}{tg\left(45^0 - \frac{\psi_1}{2}\right)} . \quad (6)$$

Taking into account the well-known formula of Professor Zvorykin K.A. [1] for determining the nominal angle of shear of the work material (in turning):

$$\beta = 45^0 - \frac{(\psi - \gamma)}{2} \quad (7)$$

which at angle α =0 is identical to equation (5), equation (6) for positive rake angle γ takes the following form:

$$\sigma = \frac{2 \cdot \tau_{shear}}{tg\beta}. \tag{8}$$

According to equations (6) and (8), the energy consumption in machining σ can be reduced uniquely by decreasing the angle ψ_1 or increasing the nominal angle of shear of the work material β. Considering the angle $\psi_1 = \psi - \gamma$ when turning, it is clear that it can be reduced by decreasing the nominal friction angle of the face surface of the tool with chips ψ and by decreasing the positive rake angle γ. Based on equation (6), the lowest value of the energy consumption in machining σ will be achieved at angle ψ_1=0, i.e. at a condition of $\psi = \gamma$, where γ – is the positive rake tool angle.

Clearly, the condition α <0 can be implemented both at edge cutting machining and grinding, reducing the energy consumption of the machining process σ. This condition is implemented, for example, at cut-down milling, especially with an end mill.

It follows from equation (8) that during turning, machining energy consumption σ is always lower than at grinding, since in this case the nominal shear angle of the work material β is greater. This follows from the formula of Professor Zvorykin K.A. [1], which at grinding applications due to negative rank angle γ on cutting grains takes the following form:

$$\beta = 45^0 - \frac{(\psi + \gamma)}{2} \tag{9}$$

Consequently, as already noted, a decrease in the negative rake angle γ of the cutting grain is the most important condition for reducing the energy consumption in machining σ. This explains the fact that it is possible to achieve a much higher performance rate in turning than in grinding, while preventing the formation of temperature defects on machined surfaces. Therefore in recent years operators utilize modern technologies that include high-speed turning and milling that provide higher productivity and machining quality, in finish machining operations instead of grinding. Particularly effective is the use of diamond turning, which due to the high sharpness of the cutting edge and the low coefficient of friction results in a dramatic reduction in cutting force and temperature and, accordingly, high-quality processing.

In addition to machining energy consumption σ, the most important parameter in the cutting process is the ratio of the tangential cutting force P_z and thrust force P_y [11]:

$$\frac{P_z}{P_y} = \frac{1}{tg(\alpha + \psi_1)}. \tag{10}$$

Table 2 and Figure 3 show the nature of the change in the ratio P_z / P_y depending on angle ψ_1.

Table 2:Design Values for the Ratio P_z / P_y

$\psi_1,^0$	**0**	**30**	**45**	**60**	**90**
α =0	∞	1.7	1.0	0.55	0
α =450	1.0	0.28	0	–	–
α = –450	–	–	∞	4.0	1.0

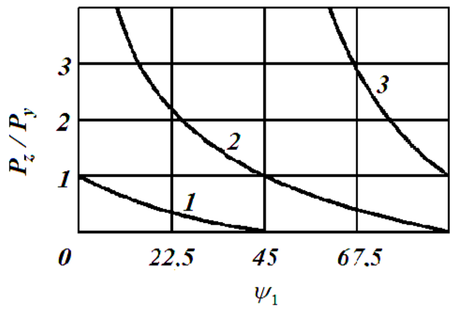

Figure 3: Angle ψ_1 Effect on the Change in Ratio P_z / P_y ;
1: α =0; 2: α =45^0; 3: α = –45^0

As it can be seen, the ratio P_z / P_y decreases as the angle ψ_1 increases, and for α =0 it is decreased within the full range of the angle change ψ_1 (from 0 to 900). With an increase of angle α (α =450) the range of angle change ψ_1 is narrowed (from 0 to 450), and for a negative value α = –450 it is removed to the range of a higher values of the angle ψ_1 (from 450 to 900). The ratio P_z / P_y reaches the largest values at negative value α = –450, when the cutting and chip formation processes are most effective, especially with increased value of the angle ψ_1 (at negative rake angle of cutting grain γ).

As follows from equation (10), with an increase in the sum of the angles $(\alpha + \psi_1)$, the ratio P_z / P_y decreases, this indicates that the thrust force P_y predominates in the force stress in the cutting process. Therefore, the ratio P_z / P_y will be greater, when grinding is compared to edge cutting machining. This is due to a larger angle ψ_1; at grinding it is equal to $\psi_1 = \psi + \gamma$ while at turning it is equal to $\psi_1 = \psi - \gamma$.

Therefore, as it is shown, there is coloration between the energy consumption in machining σ and the P_z / P_y ratio: a lower P_z / P_y ratio corresponds to a larger σ value. This is explained by the fact that when grinding the ratio P_z / P_y varies within the range 0 to 1, wherein the edge cutting, machining the ratio P_z / P_y is more than 1, with values up to 10.

The low value of the ratio P_z / P_y when grinding is due to the low ratio of the thickness of the cut a_z to the nose radius of the cutting grain R , i.e. a_z / R. It is known that the transition from the process of elastic-plastic deformation of the work material to the cutting process is possible at a ratio a_z / R equal to 0.04 to 0.08 (according to Professor Kragelsky I.V.) [5]. Therefore, in order to increase the efficiency of the cutting process, it is necessary to increase the ratios a_z / R and P_z / P_y, due to the decrease in angles α and ψ_1. This will theoretically reduce the machining energy consumption σ .

The nose radius of the cutting grain can be expressed through its negative rake angle γ (Figure 3). It requires setting the angle $\varphi = 90^0 - \gamma$ by the following condition

$$\frac{R - a_z}{R} = \cos\varphi \tag{11}$$

From which, it follows that

$$\frac{a_z}{R} = 1 - \sin\gamma \qquad (12)$$

Consequently, with an increase of the angle γ the ratio a_z / R decreases. Accordingly, this leads to a decrease in the ratio P_z / P_y and an increase in the machining energy consumption σ. As practice shows, when grinding with an acute diamond wheel, the ratio a_z / R can be increased up to 1. In this case the rake angle γ can be made to move towards zero.

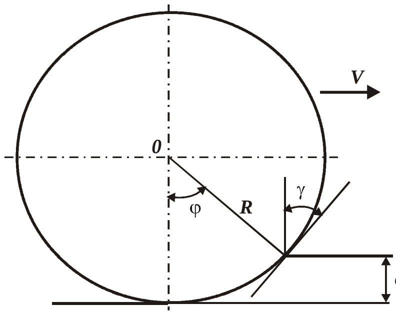

Figure 3: Design Diagram for the Ratio a_z / R

While turning, the rake angle γ takes a positive value, therefore, equation (12) can be written as:

$$\frac{a_z}{R} = 1 + \sin\gamma . \qquad (13)$$

Therefore, the ratio a_z / R is greater than 1, which also agrees with machining practices.

Based on equation (9) when $\beta = 0$, it is possible to set a maximum value of the angle $\psi_1 = \psi + \gamma$, at which the microcutting process is carried out with a single grain. It is easy to see that this condition is fulfilled at an angle $\psi_1 = 90^0$, i.e. at a negative rake angle of the cutting grain $\gamma = 90^0 - \psi$.

If the nominal friction angle of the cutting grain with the work material approaches zero $\psi \to 0$, then $\gamma \to 90^0$. In this case, the metal is actually removed with dull grains. As the angle ψ increases, the limiting negative rake angle of the cutting grain γ should be reduced, i.e. the formation of micro-cuts will occur when microcutting with a sharper grain. The ratio a_z / R based on the angle $\gamma = 90^0 - \psi$ can be represented as follows:

$$\frac{a_z}{R} = 1 - \sin\left(90^0 - \psi\right) = 1 - \cos\psi . \qquad (14)$$

As can be seen, the ratio a_z / R is clearly determined by angle ψ (Table 3, Figure 4): the more it is, the more the ratio a_z / R is. Physically, it means that according to the fact hat $\gamma = 90^0 - \psi$, the negative rake angle of the cutting grain γ decreases. This helps to improve the conditions of chip formation, to increase the ratios a_z / R and P_z / P_y, and to reduce the machining energy consumption σ.

Table 3: Design Values of Friction Coefficient $f = tg\psi$, of Negative Rake Angle of Cutting Grain γ and Ratio a_z / R

ψ [angle degree]	0	10	20	30	30	45
f	0	0.176	0.364	0.577	0.839	1.0
γ [angle degree]	90	80	70	60	50	45
a_z / R	0	0.015	0.06	0.134	0.234	0.29

As it is known, the minimum value of the ratio, at which the process of elastic-plastic deformation of the material passes into the process of cutting (when micro cutting with a single grain) according to the experimental data of Professor Bogomolov N.I. is 0.04 to 0.08 [5], and according to the experimental data of Professor Kragelsky I.V. is equal to 0.14 to 0.17 [5]. Table 3 shows that it is achieved at an angles between, which corresponds to a coefficient of friction f between 0.2 and 0.4 during abrasive grain machinating of steel. Thus, the well-known experimental results, which determine the conditions for the micro cutting process with a single grain, are theoretically justified.

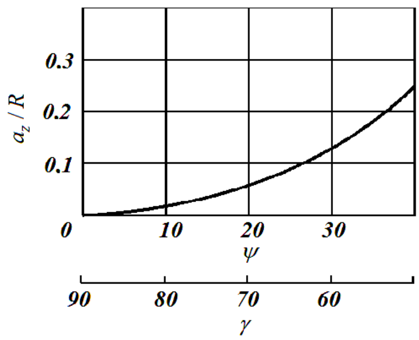

Figure 4: Dependence of Ratio a_z / R on Nominal Friction Angle of Cutting Grain with Work Material ψ (on Negative Rake Angle of Cutting Grain γ)

The condition for decreasing tangential cutting force P_z and thrust force P_y at turning can be determined based on the following equations:

$$P_z = \sigma \cdot S_{shear} \tag{15}$$

$$P_y = \frac{\sigma}{K_{cut}} \cdot S_{shear} \tag{16}$$

where K_{cut}: cutting value, which is determined by the dependence (10); $S_{shear} = S \cdot t$: cross-section area of shear [m^2]; S: feed [m/rpm]; t: cutting depth [m].

As is seen, it is possible to decrease P_z and P_y by only reducing the energy consumption in machining σ, since the decrease of the cutting mode parameters S and t leads to the reduction of the performance rate, which is ineffective. Decreasing P_y suggests decreasing σ and increasing K_{cut}. As it has been shown, σ and K_{cut} parameters are mutually opposite, increasing the impact of the angle $(\alpha + \psi_1)$, used in equations (1) and (10) on the thrust force P_y, i.e. the angle $(\alpha + \psi_1)$ has a broader impacts on P_y than on P_z.

When grinding, in equations (15) and (16), instead of the parameter S_{shear}, it is necessary to consider the instantaneous total cross-sectional area of the shear by simultaneously operating grains of the wheel $S_{inst.} = Q / V_{wheel}$ [12-14], where $Q = B \cdot V_{part} \cdot t$: is a performance rate [m^3/s]; B : is a width of grinding, m; V_{part} : is a part speed [m/s]; t : is a depth of grinding [m]; V_{wh} : is a wheel speed [m/s]. Then equations (15) and (16) can written as follows:

$$P_z = \sigma \cdot \frac{Q}{V_{wh}} \quad (17)$$

$$P_y = \frac{\sigma}{K_g} \cdot \frac{Q}{V_{wh}} \quad (18)$$

where $K_g = K_{cut}$: is a grinding ratio ($K_g < 1$).

As it follows from equations (17) and (18), the most significant reduction in the cutting force components at grinding can be achieved by increasing the speed of the wheel V_{wh}. This explains the main effect of grinding that distinguishes it from the turning. Decreasing the tangential cutting force and thrust force at grinding by increasing the speed of the wheel V_{wh} predetermines the decrease in the elastic displacements that arise in the process and increases machining accuracy. This machining effect is difficult to achieve in turning, which allows grinding to be considered as the main high-performance finishing method that ensures high accuracy figures of the surfaces being machined. However, as it is known [5], the cutting temperature at grinding is mainly determined by the energy consumption in machining σ, and not by the cutting force, so it is more difficult to achieve a high quality surface finish, excluding the formation of bones, micro cracks and other temperature defects. Thus, various methods for evaluating quality factors required to achieve accurately finished machined surfaces by grinding have been determined.

CONCLUSIONS

Conditions for reducing energy consumption in machining at grinding taking into account the angle of entry of the abrasive grain into the work material were theoretically determined. They include the change of shape of shearing micro-cuts by cutting grains: transition from the up grinding with the periphery of a wheel to the kinematic chains of the face and down grinding with the periphery of a wheel, reduction of intensity of friction of the cutting grain with work material, and the decrease of the negative rake angle of the cutting grain due to the use of wheels of superhard synthetic materials. In edge cutting machining they involve, for example, the application of tangential turning, cut-down milling with an end mill.

The range of change in the nominal friction angle of the cutting grain with the work material and the negative rake angle of the cutting grain, under which the energy consumption in machining reaches its lowest values, were determined theoretically. It is shown that the nature of the change in the energy consumption in machining is derived from the change of the nominal shear angle of the work material. It is established that infinite values of the energy consumption in machining are achieved at a nominal shear angle of the work material equal to the angle of entry of the abrasive grain into the work material. Therefore, it is necessary to increase the nominal angle of shear at the work material by reducing the friction intensity in the cutting area and the negative rake angle of the cutting grain.

The conditions for increasing the efficiency of machining by increasing the ratio of the tangential cutting force and thrust force, as well as the ratio of the shear thickness to the corner radius of the tool included angle, which reduce the

friction in the cutting area and the rake angle of the cutting tool, were determined theoretically. It is shown that it is possible to achieve a reduction in the cutting force and improve the accuracy of machining at grinding, by reducing the energy consumption in machining and substantially increasing the speed of the wheel. This predetermines the effectiveness of the use of grinding in finishing operations.

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